



HAL
open science

Elevated purification of urban rainwater runoff using a calamus constructed wetland with multi-layer carrier fillers

Anze Li, Guixia Ji, Chunlei Xu, Eric Lichtfouse, Jin Huang, Hongbo Liu

► **To cite this version:**

Anze Li, Guixia Ji, Chunlei Xu, Eric Lichtfouse, Jin Huang, et al.. Elevated purification of urban rainwater runoff using a calamus constructed wetland with multi-layer carrier fillers. *Journal of Water Process Engineering*, 2023, 56, pp.104273(1-8). <10.1016/j.jwpe.2023.104273>. <hal-04367747>

HAL Id: hal-04367747

<https://hal.science/hal-04367747v1>

Submitted on 30 Dec 2023

HAL is a multi-disciplinary open access archive for the deposit and dissemination of scientific research documents, whether they are published or not. The documents may come from teaching and research institutions in France or abroad, or from public or private research centers.

L'archive ouverte pluridisciplinaire **HAL**, est destinée au dépôt et à la diffusion de documents scientifiques de niveau recherche, publiés ou non, émanant des établissements d'enseignement et de recherche français ou étrangers, des laboratoires publics ou privés.



Distributed under a Creative Commons CC0 1.0 - Universal - International License

Elevated purification of urban rainwater runoff using a *calamus* constructed wetland with multi-layer carrier fillers

Anze Li^a, Guixia Ji^a, Chunlei Xu^b, Eric Lichtfouse^c, Jin Huang^d, Hongbo Liu^{a,*}

^a School of Environment and Architecture, University of Shanghai for Science and Technology, 200093 Shanghai, China

^b Beijing Municipal Engineering Design and Research Institute Co., Ltd., 100082 Beijing, China

^c Aix-Marseille Univ, CNRS, IRD, INRA, Coll France, CEREGE, 13100 Aix en Provence, France

^d Shanghai Urban Construction Design & Research institute(Group)Co., Ltd, 200125 Shanghai, China

ARTICLE INFO

Keywords:

Runoff
Quality fluctuation
Three filler layers
Calamus wetland
Treatment effectiveness

ABSTRACT

Urban water body pollution caused by storm-water runoff is increasingly serious due to rising global urbanization. We evaluated the effectiveness of a *calamus* vertical flow constructed wetland purifying urban runoff. This wetland was constructed using three filler layers of rare earth porcelain sand, ceramsite, and clinoptilolite respectively. The results revealed that under the optimal hydraulic load of 80 L/(m²·h), pollutants removal efficiency with the study wetland reached 89.9 %, 95.0 %, 84.7 %, and 76.2 % for the moderate rain runoff, in terms of COD (chemical oxygen demand), SS (suspended solids), TN (total nitrogen) and TP (total phosphorus) respectively. The removal rates of COD, SS, TN and TP by plants and the soil layer together were up to 64.9 %, 50.0 %, 58.1 %, and 28.6 %, respectively, while the rare earth porcelain sand layer had the highest contribution to the removal rate of TP (42.8 %), and the filler removal effect for phosphorus was more significant than that of plants and the soil layer. Although the influent water quality fluctuates with runoff from moderate to heavy torrential rain intensities, most of the effluent water meets the discharging standards. While the effluent quality of light rain runoff with high pollution load slightly exceeded the standards, it still removal rate as high as 88 %, 96.3 %, 73.3 %, 76.2 % for COD, SS, TN, TP.

1. Introduction

The pollution of urban runoff is rapidly increasing worldwide due to rising urbanization. Urban runoff is considered as the main pollution source of urban rivers, where massive pollutants in runoff is discharged into urban water bodies [1]. The urban runoff contains contaminants such as organic matter, suspended solids (SS), nitrogen, phosphorus, and heavy metal washed from air and soil [2]. For instance, in the case of Neijiang City, China, the chemical oxygen demand (COD) discharge load from a single storm reached as high as 73.7 tons (t). Based on the estimated annual rainfall of 1000 mm, the total phosphorus (TP), ammonium (NH₃-N), and total nitrogen (TN) discharges from runoffs were about 3.855 t, 41.410 t, and 69.133 t, respectively. There are significant differences in runoff quality for different regions, due to various runoff surfaces and rainfall intensities [3]. The non-point source pollution of urban runoff is considered as one of the critical factors for urban water body pollution and eutrophication [4,5]. Therefore, it is imperative to control urban runoff pollution and to prompt runoff resource utilization,

in order to counter black odor pollution and eutrophication of water bodies worldwide [6].

The constructed wetland for urban runoff management has the characteristics of high efficiency, low cost, low energy consumption, and convenient management features [7]. Compared with coagulation sedimentation, filtration, ultrafiltration and other treatment technologies, the constructed wetland (CW) technology is more adhering to the concept of low-impact development, management, and utilization. Therefore, CWs have been widely studied and applied worldwide [8]. CWs can be categorized into free surface flow (FSF), subsurface flow (SSF), tidal flow, and baffle flow artificial wetlands depending on the hydraulic level [9]. Different types of constructed wetlands can be combined with each other (i.e., hybrid or combined systems) to utilize the specific advantages of different systems. However, long-term effective treatment performance and sustainable operation of constructed wetlands remains a challenge. On the one hand, plant species and media types are key influencing factors on the removal performance of CWs as they are considered to be the main biological components of CWs and

* Corresponding author at: 516, Jungong Road, 200093 Shanghai, China.

E-mail address: Liuhb@usst.edu.cn (H. Liu).

directly or indirectly alter pollutant removal over time [10]. Herandez Crespo et al. [11] found that all three plants, *Cattail*, *Orris* and reed, had strong sorption and uptake capacity for nitrogen and phosphorus, where *Cattail* had the highest total sorption capacity for nutrients. Vymazal et al. [12] studied the effect of substrates such as zeolite, gravel and sand on wetland microorganisms and found that microbial species and numbers were significantly higher in zeolite and sand wetlands than in gravel wetlands. On the other hand, the treatment performance of constructed wetlands depends on the optimal operating parameters such as water depth, hydraulic retention time and load, feed pattern and setup design heavily, which may lead to differences in pollutant removal efficiencies between studies [13]. One of the key variables in constructed wetland studies is the hydraulic load. In terms of pollutant removal, changes in hydraulic load greatly affect the treatment effectiveness of CWs. However, frequent heavy rainfall events induced by global warming may result in much higher hydraulic load than the original design of CWs and may lead to microbial perturbations [14]. Phosphorus removal in CWs remains poor due to microbial assimilation, susceptibility of plant uptake to environmental influences, and limited filler uptake capacity [15]. In order to enhance the stability of CWs and the sustainable operation of microorganisms, *calamus* has attracted attention for providing a wider range of biomass than other aquatic plants [16]. *Calamus* possesses a well-developed root system that exudes significant amounts of sugar, alcohol, and organic carbon, which serve as valuable energy sources for microorganisms [17]. And the extension of the root system increases the void ratio of the substrate filler, improving the oxygen concentration within it [18]. This creates an optimal environment for microorganisms to thrive and improve their metabolic activity. However, few studies have used *calamus* biomass as a plant carbon source in artificial wetlands. In our previous study, we found that *calamus* was more effective in removing nitrogen, phosphorus, organic matter, and heavy metals from runoff and was more adaptable to water quality fluctuations and acidity. Also, wetland carrier fillers showed better adsorption and filtration performance for urban runoff pollutants [19].

The objectives of this study were: (1) to construct a vertically flowing artificial wetland structure utilizing *calamus*, rare earth porcelain sand, ceramsite, and clinoptilolite as carrier layers, aiming to address the pollution caused by increased urbanization and stormwater runoff resulting from heavy rainfall. (2) to assess the effectiveness of the wetland in purifying urban runoff and to explore the optimal hydraulic load for its operation, providing valuable references for the actual engineering design and operation; and (3) to investigate the denitrification and phosphorus removal mechanisms facilitated by the *calamus* and multi-filler layers in CWs, aiming to propose potential solutions to combat anaerobic black odor resulting from runoff organic pollutants and to address eutrophication caused by nitrogen and phosphorus in urban water bodies.

2. Materials and methods

2.1. Experimental water samples

Since the water volume and quality of runoff vary with the rainfall intensity and the properties of the underlying surface, five typical rainfalls with intensities from light rain to heavy torrential rain were studied. We define rainfall intensity by the amount of rainfall, which can be categorized as: light rain (0.2–10 mm day⁻¹), moderate rain (10–25 mm day⁻¹), heavy rain (25–50 mm day⁻¹), and torrential rain (≥50 mm day⁻¹). The torrential rain can be further categorized as torrential rain (50–100 mm day⁻¹), heavy torrential rain (100–250 mm day⁻¹), and very heavy torrential rain (≥250 mm day⁻¹). The above rainfall intensities were adopted by the China Meteorological Administration (CMA), with detailed information referred to the following website as http://www.cma.gov.cn/2011xzt/2012zhuant/20120928_1_1_1_1/2010052703/201212/t20121212_195616.html. Runoffs of the

corresponding rainfall intensities were collected from the urban road pavement and from the roof in the campus of the University of Shanghai for Science and Technology, then transported to storage tank as the experimental water samples. The water quality of runoff samples from light rain to heavy torrential rain is shown in Table 1. Depending on the difference of the properties of the underlying surface, the main types of stormwater collected were roof storm water runoff and roadway storm water runoff. The rainwater runoff from the roof of the building was collected using a roof siphon drainage system, directed through rainwater hoppers and pipes, and ultimately stored in the runoff storage tank. The rainfall runoff from the road was directed towards rainwater collection areas on both sides of the road. The collected rainwater was then passed through screens and filters to remove various debris such as leaves, cigarette butts, and suspended solids. After this filtration process, the rainwater flows through rainwater pipelines located on both sides of the road, leading it into a rainwater storage tank. Polyethylene was used as the tank body material and the tank were sealed in a cool and dry location to inhibit biological activity and slow down the physical volatilization and chemical reaction rate. The maximum retention time of runoffs in the tank is 2–4 days to prevent aging of the water samples.

2.2. Wetland carrier fillers and plants

We used ceramsite, rare earth porcelain sand, and clinoptilolite as wetland carrier fillers, and selected *calamus* as the wetland plant for experiments investigations (supplementary material Fig. S1: Pictures of wetland plant and fillers).

2.3. Experimental devices

The optimized combination of the selected carrier fillers and plants was used to construct an efficient vertical flow CW. The experimental wetland device was made of a long column with polyethylene, with square section dimensions of 400 × 400 mm, and the height of 1700 mm. The upper layer for the experimental device was filled with 20 cm of soil, and the *calamus* was planted in the soil. The other filler layers were filled downward from the soil layer, with rare earth porcelain sand, ceramsite, and clinoptilolite respectively; the thickness of each filler layer was 30 cm, and the lower part of the filler layers was a 5 cm retainer layer. Sampling points 1–4 from bottom to top were located at the junction of different filler layers. The runoff water entered at the top of the device, and a drainage pipe was installed at the bottom to discharge the treated water. In addition, there were runoff storage tanks, pumps, flow meters, valves and other equipment devices (Fig. 1).

2.4. Experimental operations

Due to the considerable variation in runoff volume and water quality, we focused on the adaptation of the CW to fluctuations in runoff water volume and water quality, determined the optimum hydraulic load (infiltration rate) and tolerable pollution load, and analyzed the

Table 1
Water quality of runoffs with different rainfall intensities in the study.

| Rainfall intensity | Chemical oxygen demand mg/L | Suspended solids mg/L | Total N mg/L | Total P mg/L |
|-----------------------|-----------------------------|-----------------------|--------------|--------------|
| Light rain | 516.0 ± 3.0 | 623.0 ± 5.0 | 8.62 ± 0.08 | 2.35 ± 0.02 |
| Moderate rain | 356.0 ± 1.2 | 400.0 ± 1.7 | 6.20 ± 0.05 | 2.10 ± 0.02 |
| Heavy rain | 271.0 ± 0.7 | 284.0 ± 0.4 | 3.90 ± 0.03 | 1.40 ± 0.01 |
| Torrential rain | 156.0 ± 0.4 | 165.0 ± 0.3 | 2.12 ± 0.02 | 0.86 ± 0.01 |
| Heavy torrential rain | 84.0 ± 0.1 | 102.0 ± 0.2 | 1.52 ± 0.02 | 0.59 ± 0.01 |

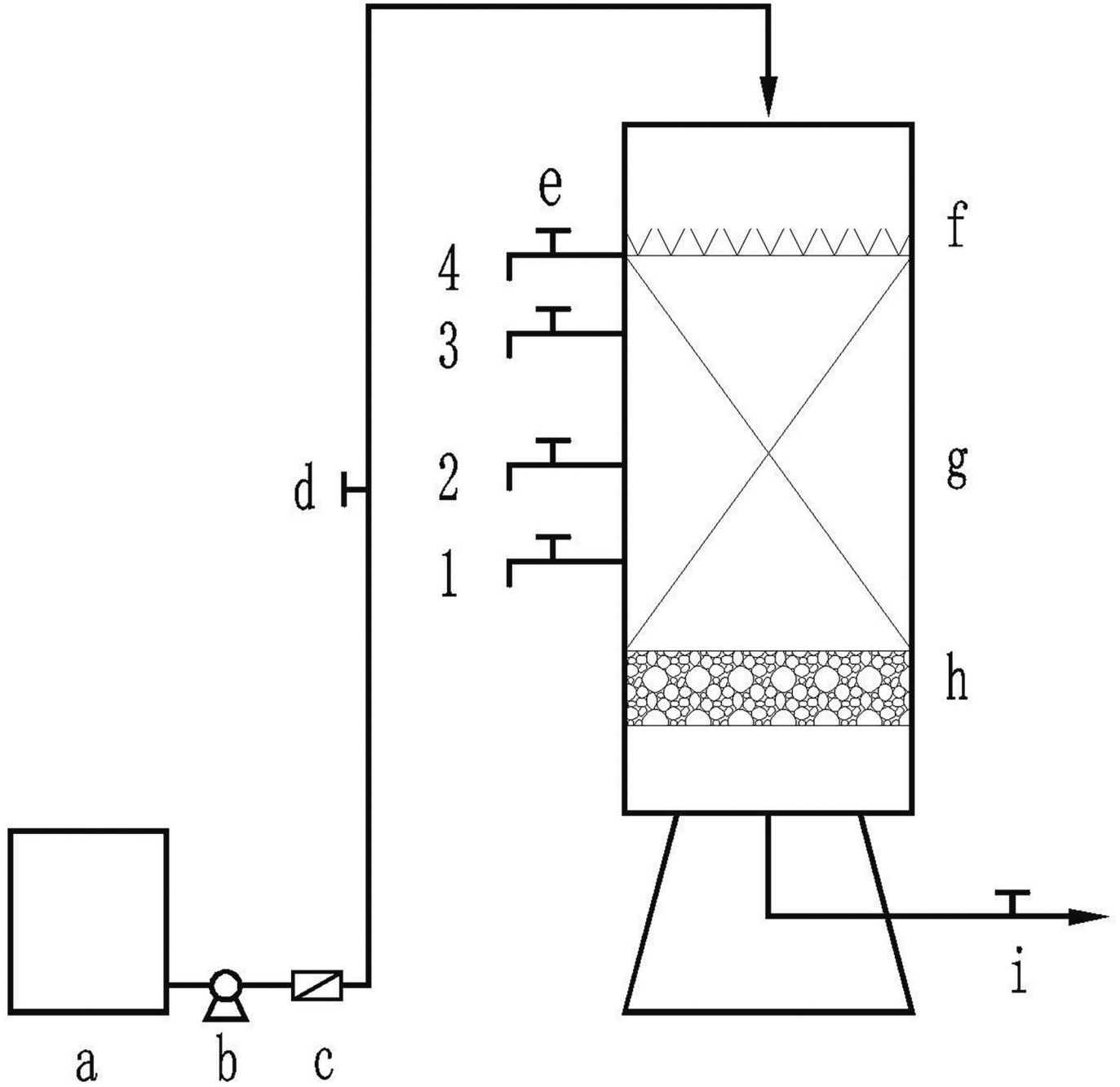


Fig. 1. Diagram of the experimental device: (a) Runoff water tank; (b) pump; (c) flow meter; (d) valve; (e) sampling points; (f) *calamus*; (g) multi-carrier fillers; (h) retainer layers; (i) treated water outlet; numbers 1–4 stands for the sampling points 1–4.

effect of runoff pollutants removal along the filler layers. The investigation was divided into three parts, and the first part was to change the influent flow rate and adjust the hydraulic load from $40 \text{ L}/(\text{m}^2 \cdot \text{h})$ to $60 \text{ L}/(\text{m}^2 \cdot \text{h})$, $80 \text{ L}/(\text{m}^2 \cdot \text{h})$, $100 \text{ L}/(\text{m}^2 \cdot \text{h})$ and $120 \text{ L}/(\text{m}^2 \cdot \text{h})$ respectively, while maintaining the basic stability of the influent water quality. After the effluent quality from continuous operations was stable at each hydraulic load, samples were taken to determine COD, SS, TN and TP. Runoffs with five intensities were used to investigate effects of fluctuations in runoff water quality on performances of CWs, from light rain to heavy torrential rain under the optimal hydraulic loads (Table 1). Water samples were taken along filler layers from the sampling points after the effluent water quality was stable.

2.5. Monitoring and analysis methods

The main pollution indicators of the experimental water samples were determined by standard methods (APHA 2005) [20], where COD was measured by a DR/2500 Hach meter, SS by the weight method, TN by potassium persulfate digestion UV spectrophotometry, TP by molybdenum antimony anti-spectrophotometry, and the experimental results were analyzed by Origin. The removal rate of each pollutant was calculated by Eq. (1).

$$E_n = \frac{C_0 - C_i}{C_0} \times 100\% \quad (1)$$

where E_n stands for removal rate (%); C_0 stands for influent concentration of a specific pollutant (mg/L); C_i stands for effluent

concentration of a specific pollutant (mg/L).

3. Results and discussion

3.1. Effect of hydraulic loads on runoff treatments

Hydraulic load is one of the key variables for CW operation [21]. In terms of pollutant removal, changes in hydraulic load greatly affect the treatment effectiveness of artificial wetlands. Suspended solids and organic matter in the CW matrix can exhibit excellent buffering capacity when the hydraulic load was increased from 750 to 1500 L/(m²·d) [22]. However, frequent heavy rainfall events brought about by global warming may result in much higher hydraulic residence times than the original design of artificial wetlands and may lead to microbial perturbation. In addition, the interaction between plant species and hydraulic load had a significant effect on the removal of each pollutant and was strongly influenced by hydraulic load. In view of the current shortage of knowledge, we selected the hydraulic load from 40 L/(m²·h) gradually increased by 120 L/(m²·h), i.e., from 960 L/(m²·d) gradually increased to 2880 L/(m²·d). After continuous operation under each hydraulic load and after the effluent quality was stable, water samples were taken from the outlet of the drainage pipe to determine the COD, SS, TN and TP of the treated water and to calculate the removal rate of each pollutant. Detailed results are shown in Fig. 2.

With the increase of hydraulic load from 40 L/(m²·h) to 120 L/(m²·h), the COD removal rate of the study system decreased from 89.4 % to 72.0 %. At a hydraulic load of 80 L/(m²·h), the runoff COD removal rate was approximately 86.0 %, and the COD concentration of the

effluent was about 38.0 mg/L (Fig. 2a). The effluent COD met the Water Quality Standards for River Landscape Environment in China (GB/T 18921-2019). When the hydraulic load exceeded 80 L/(m²·h) and continued to increase, the COD removal rate decreased rapidly; when the hydraulic load increased to 100 L/(m²·h), the effluent COD concentration was deteriorated to about 69.0 mg/L.

Hydraulic loads changing from 40 L/(m²·h) to 120 L/(m²·h) had no significant effect on SS removal of the system (Fig. 2b). However, Fig. 2 (c) indicated that the removal rate of TN decreased with the increased hydraulic load. When the hydraulic load increased from 40 to 120 L/(m²·h), the TN removal rate decreased from 92.6 % to 75.7 %, and the TN concentration in the treated effluent increased from 0.3 mg/L to 1.1 mg/L correspondingly. TN in effluent was <2.0 mg/L, and the effluent water quality met the discharging standard. Effluent TP also decreased with the increase of hydraulic load. When the hydraulic load increased from 40 L/(m²·h) to 120 L/(m²·h), the TP removal rate decreased from 80.8 % to 58.5 %. When the hydraulic load was 80 L/(m²·h), the TP removal rate was 75.0 %, and the effluent TP concentration was about 0.4 mg/L (Fig. 2d). The removal rate of TP decreased rapidly when the hydraulic load was further increased from 80 L/(m²·h) to higher loads; at a hydraulic load of 120 L/(m²·h), the effluent TP concentration was about 0.6 mg/L, slightly exceeded the discharging standard.

The hydraulic load is not only affected by the wetland surface area, water depth and filler porosity, but also may be affected by the physiological growth characteristics of plants, while the developed root system of plants can improve the hydraulic efficiency of CWs, which has a greater impact on the hydraulic characteristics. However, hydraulic load, as an important indicator of hydraulic properties, and its

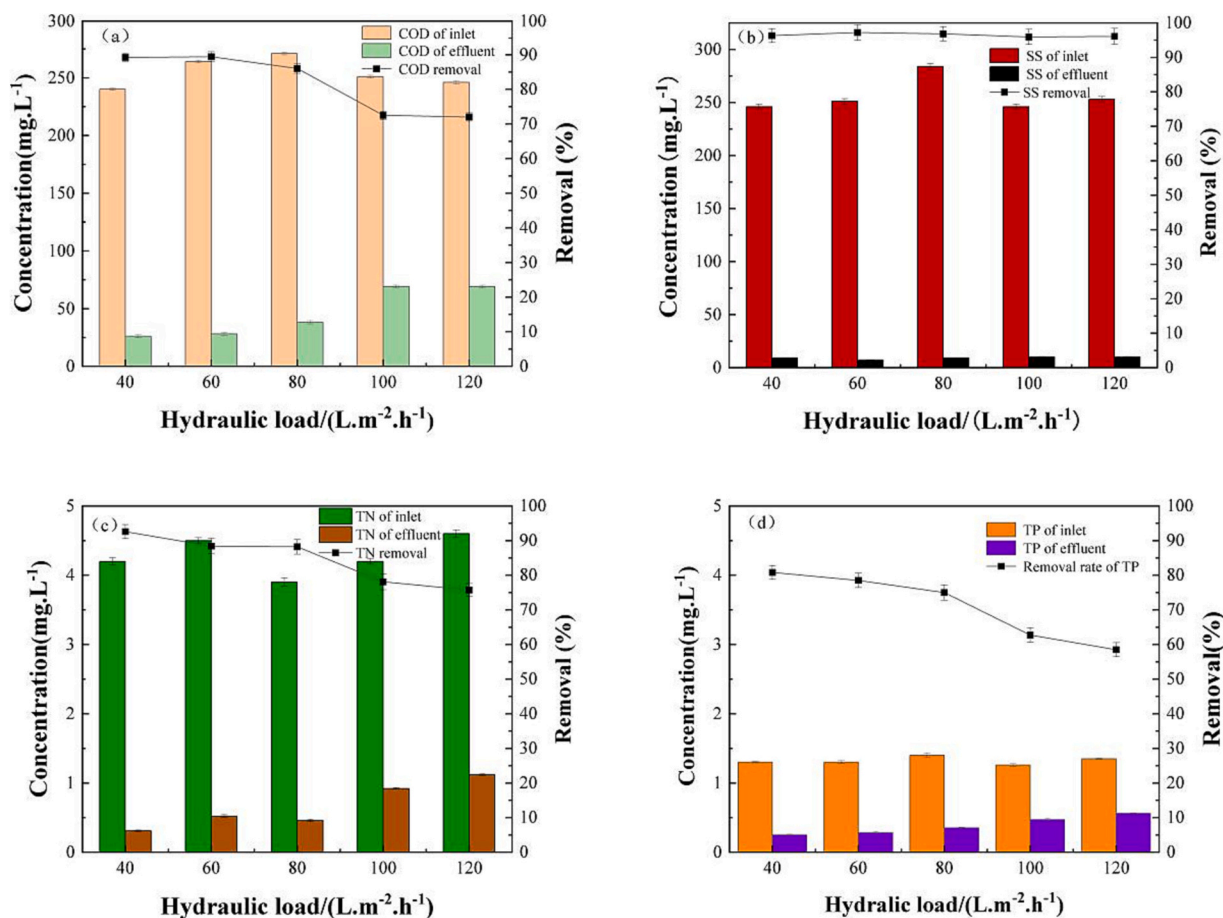


Fig. 2. Effects of hydraulic load on the removal of COD, SS, TN and TP of the runoff (a) the influent and effluent concentrations of COD and its removal rate; (b) the influent and effluent concentrations of SS and its removal rate; (c) the influent and effluent concentrations of TN and its removal rate; (d) the influent and effluent concentrations of TP and its removal rate.

interaction with plant root system will also affect the removal of pollutants in artificial wetlands. The removal rate of runoff pollutants in the wetland decreased as the hydraulic load increased. This was mainly because the pollutants in the runoff were not sufficiently absorbed by plants, or adsorbed by carrier fillers, nor sufficiently degraded by microorganisms as the hydraulic load increased and the hydraulic retention time decreased [23]. In the early stages of growth, *Calamus* presents a relatively low capacity in pollutants adsorption due to its underdeveloped root system. The limited surface area of the young plant's roots restricts its contact with pollutants in the soil. As the *calamus* grows, the root system gradually expands, increasing the surface area available for contact with contaminants. When the inlet water flow was too big and the hydraulic load exceeded the capacity of the wetland, the effluent quality was deteriorated [24]. At a hydraulic load of about 80 L/(m²·h), the effluent COD, SS, TN, and TP of the study wetland could meet the discharging standard. Therefore, the optimal hydraulic load of this constructed wetland runoff treatment was 80 L/(m²·h).

3.2. Adaptability of the study wetland to fluctuation in runoff water qualities

To study the tolerance of the wetland to the influent pollution loads, runoffs with different water qualities (Table 1) entered the wetland treatment separately with a hydraulic load of 80 L/(m²·h). The wetland system operated continuously under each runoff water quality, and after the effluent water quality was stabilized, samples were taken from the outlet of the drainage pipe to determine COD, SS, TN and TP of the effluent water. The results are shown in Fig. 3.

With the fluctuation of runoff water quality and the change of pollutant load in the influent, the change of COD removal rate ranged from 84.5 % to 89.9 %. The average COD concentrations of moderate, heavy, torrential and heavy torrential rain runoffs were 356.0, 271.0,

156.0 and 84.0 mg/L respectively (Table 1), and the COD concentrations of the treated effluent were 36.0, 38.0, 20.0 and 13.0 mg/L respectively (Fig. 3a). The COD index of the treated effluent was significantly better than the Water Quality Standards for River Landscape Environmental in China. When the COD concentration of the light rain runoff was higher at 516.0 mg/L, the COD concentration of the treated effluent was 62.0 mg/L (>60.0 mg/L), indicating that the organic pollution load of the light rain runoff had exceeded the treatment capacity of the wetland to meet the discharging standards.

The wetlands' removal efficiency range of the runoff SS was 90.2–96.8 % with the fluctuation of runoff water quality. The SS concentrations of the treated effluent from moderate, heavy, torrential and heavy torrential rain runoff were about 20.0, 9.0, 12.0 and 10.0 mg/L respectively (Fig. 3b), all of which were <20.0 mg/L, which could meet the Water Quality Standards for Reuse of Reclaimed Water in Landscape Water Bodies in China. Although the SS removal rate of light rain runoff by the wetland was as high as 96.3 %, the SS concentration in the treated effluent was 23.0 mg/L (>20.0 mg/L); the results showed that the suspended solids in light rain runoff also exceeded the treatment capacity of the wetland to meet the discharging standards.

As the rainfall intensity increased, the TN concentration in the runoff decreased and the TN removal efficiency initially increased before subsequently decreasing, with the highest TN removal rate of about 89.2 % in the wetland for torrential rain runoff (Fig. 3c). This pattern was a result of the dominant role of microorganism degradation in constructed wetlands for TN removal, followed by plant uptake and filler adsorption. Nitrogen in sewage is mainly absorbed by plants in the form of NO₃⁻-N and NH₄⁺-N. *calamus* can absorb and convert nitrogen into plant tissue components through assimilation during the growth process, and then harvest the plants manually to achieve the effect of nitrogen removal. In addition, the well-developed root conditions of *calamus* can create an inter-root environment suitable for the growth of

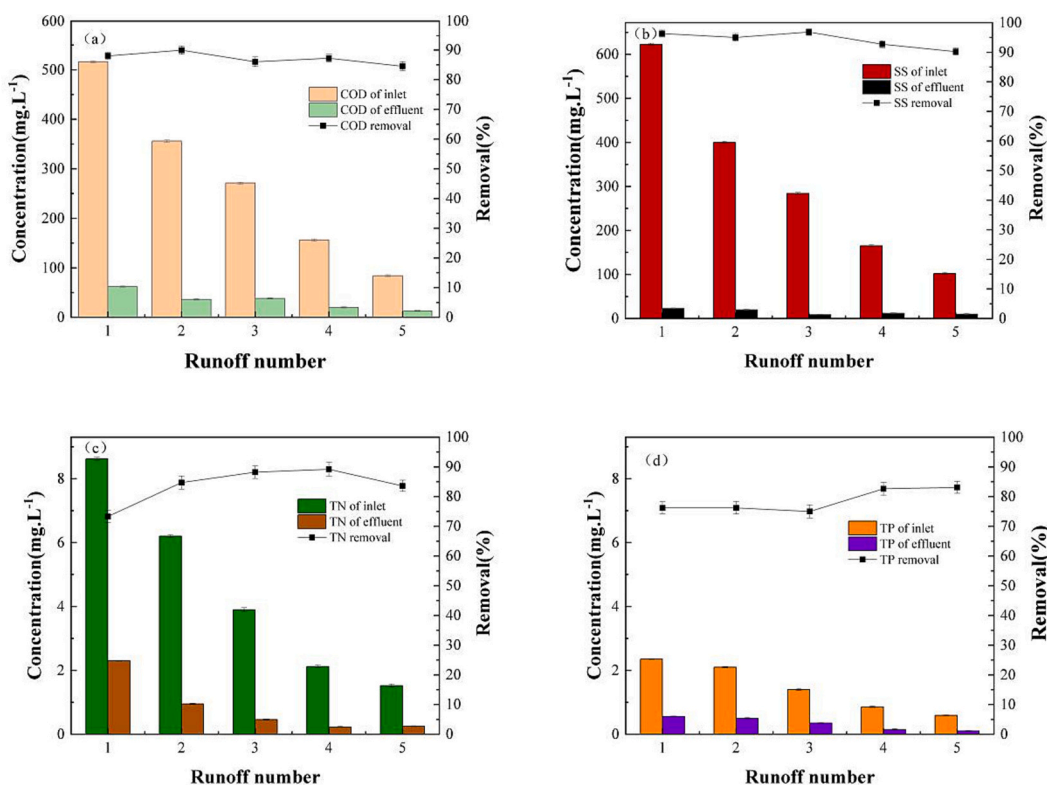


Fig. 3. Effects of runoff water quality fluctuation on the removal rates of COD, SS, TN and TP (a) The influent and effluent concentrations of COD and its removal rate; (b) the influent and effluent concentrations of SS and its removal rate; (c) the influent and effluent concentrations of TN and its removal rate; (d) the influent and effluent concentrations of TP and its removal rate. The runoff No.1 stands for light rain; the runoff No.2 stands for moderate rain; the runoff No.3 stands for heavy rain; the runoff No.4 stands for torrential rain and the runoff No.5 stands for heavy torrential rain.

microorganisms, which can be utilized to achieve the removal of nitrogen [16]. The root micro-environment is the main factor affecting $\text{NH}_4^+\text{-N}$ removal. In constructed wetlands, nitrogen is first converted from $\text{NH}_4^+\text{-N}$ to $\text{NO}_3^-\text{-N}$ through nitrification, and then further converted to N_2 and NO through denitrification and discharged into the water column (Fig. 4). When the TN concentration in runoff was too low and the nitrogen nutrients for biological growth and reproduction were insufficient, or when it became too high and exceeded the needs of microorganisms and plants, the TN removal efficiency would decrease in both scenarios [25]. The removal rate of TN in runoff by this wetland was 73.3–89.2 %, and the treated effluent TN concentrations of five runoffs (Table 1) from light rain to heavy torrential rain were 2.30, 0.95, 0.46, 0.23 and 0.25 mg/L, respectively, all of which could meet the Water Quality Standards for Reuse of Reclaimed Water in Landscape Water Bodies in China.

The phosphorus removal efficiency of the wetland for the runoff was 75.0–83.1 %. Soil and filler layers adsorption and chemical reaction played a dominant role in phosphorus removal [26–28]. With the increase of rainfall intensity, the TP concentration in the runoff decreased, and the TP concentration in the treated effluent decreased from 0.56 mg/L to 0.10 mg/L (Fig. 3d). Only the TP concentration in the treated effluent of light rain runoff slightly exceeded the standard, which was 0.56 mg/L (>0.50 mg/L). The TP concentrations in the treated effluent from moderate rain to heavy torrential rain runoffs met the Water Quality Standard for Reuse of Reclaimed Water in Landscape Water Bodies in China.

From the above analysis, it could be seen that the wetland was highly adaptable to water quality fluctuations of moderate, heavy, torrential and heavy torrential rain runoff, and the treated effluent water quality had been kept excellent and stable. The pollution load of light rain runoff slightly exceeded the treatment capacity of the wetland to meet discharging standards. However, the removal rates of COD, SS, TN and TP of the wetland for light rain runoff were still as high as 88.0 %, 96.3 %, 73.3 % and 76.2 %, respectively (Fig. 3), which greatly reduced the pollutants discharged from runoffs.

3.3. Removal effectiveness of runoff pollutants along the carrier filler layers

After the effluent water quality was stable, samples from sampling points 1–4 were taken to determine its COD, SS, TN, and TP indicators.

Effects of pollutant removal by each carrier filler layer were shown in Fig. 5.

The removal rate of each pollutant in the runoff increased with the thickness of the packing layers. The total removal rates of COD, SS, TN and TP were as high as 89.9 %, 95.0 %, 84.7 % and 76.2 %, among which the removal rates of COD, SS, TN and TP in plants and soil layer were 64.9 %, 50.0 %, 58.1 % and 28.6 % respectively. The removal rates were 12.9 %, 25.0 %, 16.1 %, and 42.8 % by the rare earth porcelain sand layer, which was relatively higher than by the ceramicsite layer and clinoptilolite layer, respectively (Table 2).

It could be inferred that soil microorganisms played the most important role in COD degradation and removal due to the presence of microorganisms such as bacteria, actinomycetes, fungi, and nitrifying and denitrifying bacteria in the soil. Nitrification and denitrification by soil microorganisms and nitrogen removal by *calamus* uptake were significant [29]. The adsorption and removal of COD and TN by the fillers were relatively insignificant. The particle size of the wetland fillers was configured increasing from top to bottom as soil particle size <2 mm, rare earth porcelain sand particle size 2–4 mm, ceramicsite particle size 3–6 mm and clinoptilolite particle size 3–6 mm. The suitable particle size gradation of fillers made it have a good filtration effect on SS. Generally, the SS removal rate of the study system was high, especially in the soil layer with small voids where the SS removal rate was the highest. In contrast, the removal efficiency of TP by the rare earth porcelain sand layer reached 42.8 %, which was higher than that by plants and soil layers. The main reason was that the removal effect of phosphorus by soil microorganism was relatively weak [30]. The rare earth porcelain sand was multi-microporous and had a large specific surface area, which had a high adsorption and removal rate on phosphorus and other pollutants. The composition of rare earth porcelain sand included SiO_2 , Al_2O_3 , Fe_2O_3 , CaO , and MgO , which could be dissolved in water and form cationic calcium, magnesium, iron, aluminum, and other substances, form insoluble phosphate precipitation and improve the phosphorus removal rate. In addition, it also had active sites such as aluminum and silicon, with a large number of Si-O-Si bonds and Al-O-Al bonds on the surface, which had a strong chemisorption effect on phosphate and further increased the TP removal efficiency (Fig. 6). When the moderate rain runoff was treated and stabilized in the wetland, the concentrations of COD, SS, TN, and TP in the treated effluent were about 36.0 mg/L, 20.0 mg/L, 0.9 mg/L, and 0.5 mg/L, respectively, which met the Water Quality Standards for Reuse

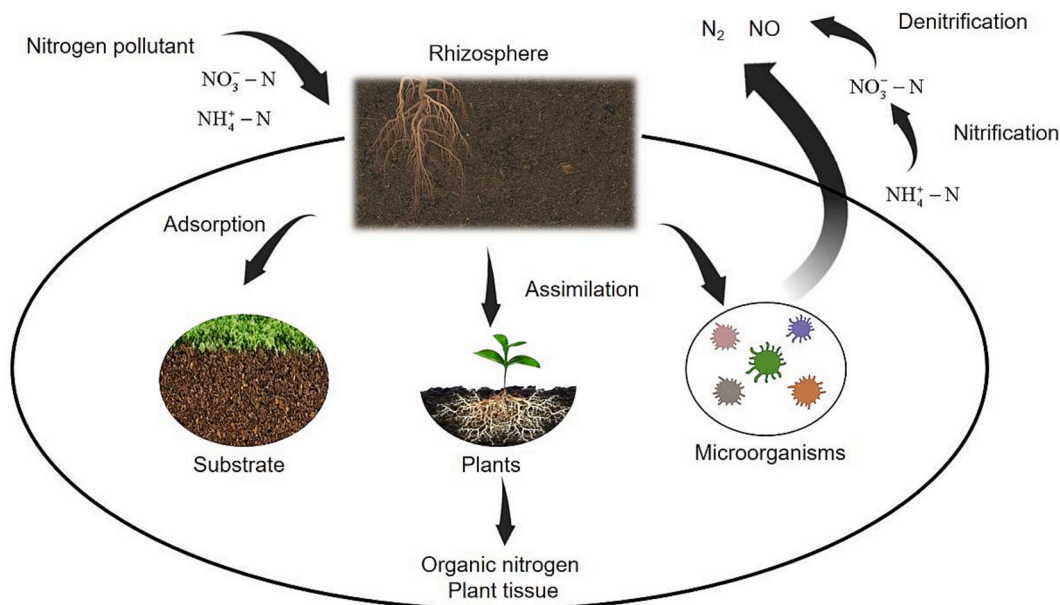


Fig. 4. Mechanism of nitrogen removal from plant root environment in constructed wetlands.

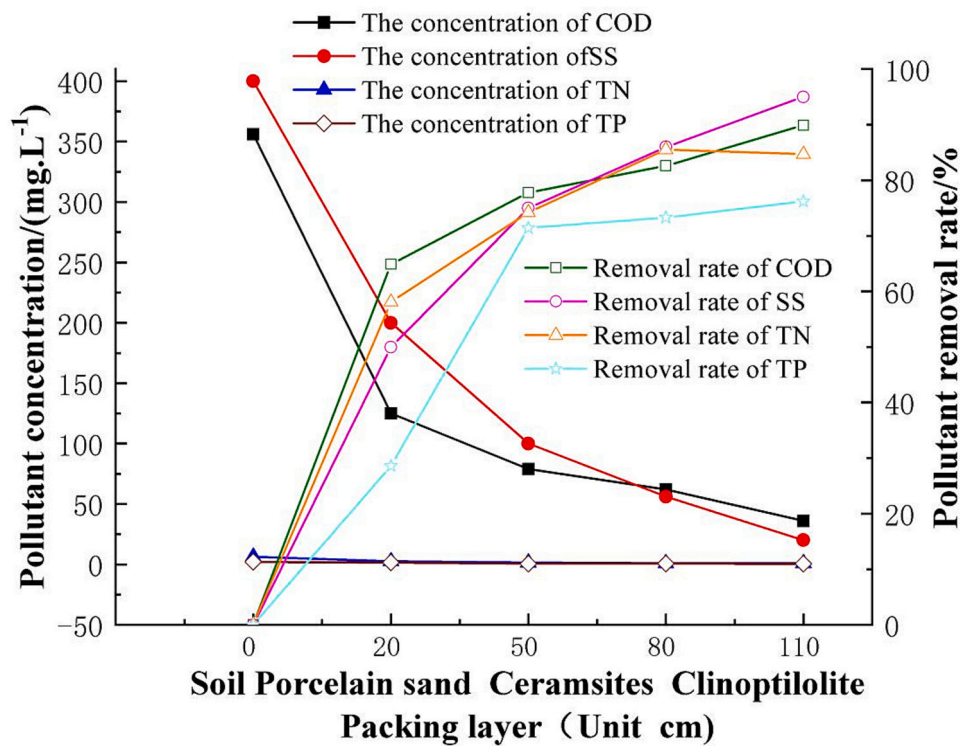


Fig. 5. Removal rates of runoff pollutants by the study wetland system along carrier filler layers.

Table 2

Average pollutant adsorption rate of each filler layer.

| | COD mg/L | COD sorption rate % | SS mg/L | SS sorption rate % | TN mg/L | TN sorption rate % | TP mg/L | TP sorption rate % |
|---------------------------|----------|---------------------|---------|--------------------|---------|--------------------|---------|--------------------|
| Influent water | 356 | 0 | 400 | 0 | 6.2 | 0 | 2.1 | 0 |
| Plant soil layer | 125 | 64.9 | 200 | 50 | 2.6 | 58.1 | 1.5 | 28.6 |
| Rare earth porcelain sand | 79 | 12.9 | 100 | 25 | 1.6 | 16.1 | 0.6 | 42.8 |
| Ceramsite | 62 | 4.8 | 56 | 11 | 0.9 | 11.3 | 0.56 | 1.9 |
| Clinoptilolite | 36 | 7.3 | 20 | 9 | 0.95 | -0.8 | 0.5 | 2.9 |

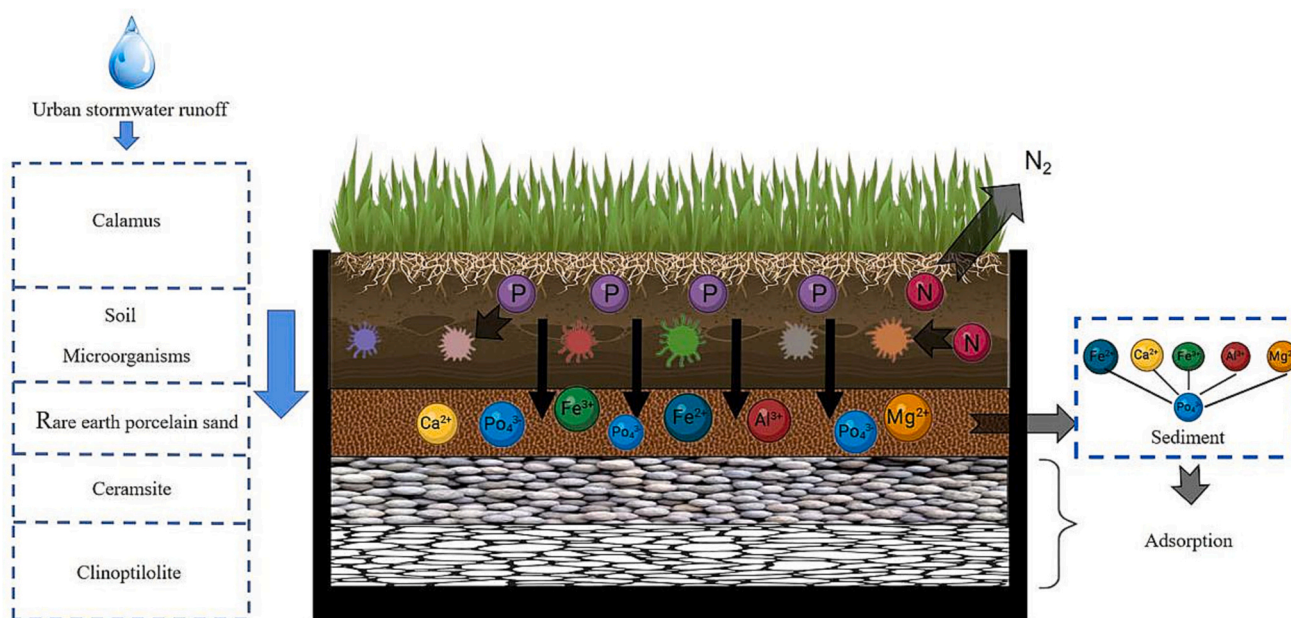


Fig. 6. Diagram elaboration of pollutants removal mechanisms by soil and filling layers of the study constructed wetland system.

Reclaimed Water in Landscape Water bodies in China and achieved landscape reuse of stormwater runoff.

4. Conclusions

A systematic evaluation of the treatment efficacy of constructed multilayer packed *calamus* wetlands for urban stormwater runoff treatment was carried out. The studied constructed wetland presented excellent adaptability to variations in rainfall intensities and fluctuations in runoff water quality. The effluent generated from moderate, heavy, torrential, and torrential heavy rainfalls remained stable and can meet the Water Quality Standards for Reuse of Reclaimed Water in Landscape Water Bodies in China. To address the variation in hydraulic load resulting from heavy rainfall events caused by global warming, the optimal hydraulic load for the operation of the *calamus* wetland was determined as 80 L/(m² h), which provides a reference for the actual project design and operation. The feasibility of removing nitrogen, phosphorus, and organic matter from runoff by using *calamus* biomass as a plant carbon source in constructed wetlands was analyzed and confirmed at the mechanistic level. In summary, the studied wetland system achieved a high-efficiency removal of runoff pollutants, bring about a significant reduction in pollutant discharge. The developed technology could be an effective tool to control organic black odor and nitrogen and phosphorus eutrophication pollution of urban water bodies.

Supplementary data to this article can be found online at <https://doi.org/10.1016/j.jwpe.2023.104273>.

Declaration of competing interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

Data availability

Data will be made available on request.

Acknowledgments

The authors would like to acknowledge the co-funding of this work by the National Natural Science Foundation of China (No. 52070130) and the Natural Science Foundation of Shanghai (No. 22ZR1443200).

References

- [1] S.J. McGrane, Impacts of urbanisation on hydrological and water quality dynamics, and urban water management: a review, *Hydrol. Sci. J.* 61 (2016) 2295–2311, <https://doi.org/10.1080/02626667.2015.1128084>.
- [2] Müller, H. Österlund, J. Marsalek, M. Viklander, The pollution conveyed by urban runoff: a review of sources, *Sci. Total Environ.* 709 (2019), 136125, <https://doi.org/10.1016/j.scitotenv.2019.136125>.
- [3] Y. Jiang, C. Zevenbergen, Y. Ma, Urban pluvial flooding and stormwater management: a contemporary review of China's challenges and "sponge cities" strategy, *Environ. Sci. Pol.* 80 (2018) 132–143, <https://doi.org/10.1016/j.envsci.2017.11.016>.
- [4] S.J. Livesley, E.G. McPherson, C. Calafpietra, The urban forest and ecosystem services: impacts on urban water, heat, and pollution cycles at the tree, street, and city scale, *J. Environ. Qual.* 45 (1) (2016) 119–124, <https://doi.org/10.2134/jeq2015.11.0567>.
- [5] Y. Ma, H. Zhao, The role of spatial patterns of low impact development in urban runoff pollution control within parcel based catchments, *Front. Environ. Sci.* (2022), <https://doi.org/10.3389/fenvs.2022.926937>.
- [6] J. Ji, J. Gao, L. Xing, X. Liu, High-resolution mapping of the rainfall runoff pollution: case study of Shiwuli River watershed, China, *Environ. Sci. Pollut. Res. Int.* 30 (2022) 28935–28946, <https://doi.org/10.1007/s11356-022-24171-6>.
- [7] J.C. Alihan, M.C. Maniquiz-Redillas, J. Choi, P.E.D. Flores, L.-H. Kim, Characteristics and fate of stormwater runoff pollutants in constructed wetlands, *J. Wetlands Res.* 19 (2017) 37–44, <https://doi.org/10.17663/jwr.2017.19.1.037>.
- [8] D. Parde, A. Patwa, A. Shukla, R. Vijay, D.J. Killedar, R. Kumar, A review of constructed wetland on type, treatment and technology of wastewater, *Environ. Technol. Innov.* 21 (2021), 101261, <https://doi.org/10.1016/j.eti.2020.101261>.
- [9] H. Wu, J. Zhang, H.h. Ngo, W. Guo, Z. Hu, S. Liang, et al., A review on the sustainability of constructed wetlands for wastewater treatment: design and operation, *Bioresour. Technol.* 175 (2015) 594–601, <https://doi.org/10.1016/j.biortech.2014.10.068>.
- [10] N. Zhang, D. Lu, P. Kan, J. Yangyao, Z. Yao, D.Z. Zhu, et al., Impact analysis of hydraulic loading rate on constructed wetland: insight into the response of bulk substrate and root-associated microbiota, *Water Res.* 216 (2022) 118337, <https://doi.org/10.1016/j.watres.2022.118337>.
- [11] C. Hernández-Crespo, N. Oliver, J. Bixquert, S. Gargallo, M. Martín, Comparison of three plants in a surface flow constructed wetland treating eutrophic water in a Mediterranean climate, *Hydrobiologia* 774 (2015) 183–192, <https://doi.org/10.1007/s10750-015-2493-9>.
- [12] J. Vymazal, Y. Zhao, Ú. Mander, Recent research challenges in constructed wetlands for wastewater treatment: a review, *Ecol. Eng.* 169 (2021), 106318, <https://doi.org/10.1016/j.ecoleng.2021.106318>.
- [13] S. Katakai, S. Chatterjee, M.G. Vairale, S.K. Dwivedi, D.K. Gupta, Constructed wetland, an eco-technology for wastewater treatment: a review on types of wastewater treated and components of the technology (macrophyte, biofilm and substrate), *J. Environ. Manag.* 283 (2021), 111986, <https://doi.org/10.1016/j.jenvman.2021.111986>.
- [14] J. Richardson, H. Feuchtmayr, C. Miller, P.D. Hunter, S.C. Maberly, L. Carvalho, Response of cyanobacteria and phytoplankton abundance to warming, extreme rainfall events and nutrient enrichment, *Glob. Chang. Biol.* 25 (2019) 3365–3380, <https://doi.org/10.1111/gcb.14701>.
- [15] M.X. Lima, K.Q. Carvalho, F.H. Passig, A.C. Borges, T.C. Filipe, J.C. Azevedo, et al., Performance of different substrates in constructed wetlands planted with *E. crassipes* treating low-strength sewage under subtropical conditions, *Sci. Total Environ.* 630 (2018) 1365–1373, <https://doi.org/10.1016/j.scitotenv.2018.02.342>.
- [16] C. Fan, S. He, S. Wu, J. Huang, Improved denitrification in surface flow constructed wetland planted with *calamus*, *J. Clean. Prod.* 291 (2021), 125944, <https://doi.org/10.1016/j.jclepro.2021.125944>.
- [17] Y. Wang, Z. Wang, L.-p. Wang, J. Peng, X. Kou, L.-f. Gao, et al., Effects of *calamus*-derived biochar on the thermophilic anaerobic digestion of long-SRT waste activated sludge from the municipal wastewater treatment plant, *Waste Biomass Valoriz.* 13 (2022) 2979–2989, <https://doi.org/10.1007/s12649-022-01693-1>.
- [18] C. Yang, M. Wang, H. Chen, J. Li, Responses of butachlor degradation and microbial properties in a riparian soil to the cultivation of three different plants, *J. Environ. Sci.* 23 (2011) 1437–1444, [https://doi.org/10.1016/S1001-0742\(10\)60604-3](https://doi.org/10.1016/S1001-0742(10)60604-3).
- [19] Z. Wan, Y. Zhang, S. Lu, X.-q. Zhang, X. Liu, Y. Yang, Effect of packing substrates on the purification of municipal wastewater treatment plant effluent, *Environ. Sci. Pollut. Res. Int.* 27 (2020) 15259–15266, <https://doi.org/10.1007/s11356-020-08068-w>.
- [20] American Public Health Association, Standard Methods for the Water and Wastewater, 21st ed., American Water Works Association and Water Environment Federation, Washington, D.C., 2005.
- [21] A.I. Stefanakis, V.A. Tsihrintzis, Effects of loading, resting period, temperature, porous media, vegetation and aeration on performance of pilot-scale vertical flow constructed wetlands, *Chem. Eng. J.* 181 (2012) 416–430, <https://doi.org/10.1016/j.cej.2011.11.108>.
- [22] W.H. Bang, Y. Jung, J.W. Park, S. Lee, S.K. Maeng, Effects of hydraulic loading rate and organic load on the performance of a pilot-scale hybrid VF-HF constructed wetland in treating secondary effluent, *Chemosphere.* 218 (2019) 232–240, <https://doi.org/10.1016/j.chemosphere.2018.11.110>.
- [23] H. Wu, J. Zhang, H.h. Ngo, W. Guo, Z. Hu, S. Liang, et al., A review on the sustainability of constructed wetlands for wastewater treatment: design and operation, *Bioresour. Technol.* 175 (2015) 594–601, <https://doi.org/10.1016/j.biortech.2014.10.068>.
- [24] H. Wang, J.W. Chen, X.J. Li, Removal of contaminant under different hydraulic loading rate in constructed wetland, *Asian J. Chem.* 25 (2013) 6443–6444, <https://doi.org/10.14233/ajchem.2013.14182>.
- [25] R. Wang, X. Zhao, H. Liu, H. Wu, Elucidating the impact of influent pollutant loadings on pollutants removal in agricultural waste-based constructed wetlands treating low C/N wastewater, *Bioresour. Technol.* 273 (2019) 529–537, <https://doi.org/10.1016/j.biortech.2018.11.044>.
- [26] N. Dell'Osbel, G.S. Colares, G.A. Oliveira, M.P.d. Souza, C.V. Barbosa, Ê. L. Machado, Bibliometric analysis of phosphorus removal through constructed wetlands, *Water Air Soil Pollut.* 231 (2020) 1–18, <https://doi.org/10.1007/s11270-020-04513-1>.
- [27] S. Shen, X. Li, F. Cheng, X. Zha, X. Lu, Review: recent developments of substrates for nitrogen and phosphorus removal in CWs treating municipal wastewater, *Environ. Sci. Pollut. Res. Int.* (2020) 1–19, <https://doi.org/10.1007/s11356-020-08808-y>.
- [28] C. Xu, Y.-L. Feng, H.-r. Li, Y. Yang, R. Wu, Research progress of phosphorus adsorption by attapulgite and its prospect as a filler of constructed wetlands to enhance phosphorus removal from mariculture wastewater, *J. Environ. Chem.* 10 (2022), <https://doi.org/10.1016/j.jece.2022.108748>.
- [29] J. Chang, D. Liu, H.Q. Cao, S.X. Chang, X.Y. Wang, C.C. Huang, et al., NO₃/NH₄⁺ ratios affect the growth and N removal ability of *Acorus calamus* and *Iris pseudacorus* in a hydroponic system, *Aquat. Bot.* 93 (2010) 216–220, <https://doi.org/10.1016/j.aquabot.2010.08.002>.
- [30] T. Ahmad, K. Ahmad, M. Alam, Sustainable management of water treatment sludge through 3R' concept, *J. Clean. Prod.* 124 (2016) 1–13, <https://doi.org/10.1016/j.jclepro.2016.02.073>.